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This program has been successful at demonstrating for the first time that strained AlGaInAs quantum well lasers grown by MBE can exhibit superior reliability to AlGaAs quantum well lasers. The benefits to device performance justify undertaking the development of a commmercial process to bring this improved reliability to the market for DOD applications.

There were 11 quantum well wafers characterized to help guide the selection of optimum growth conditions and to understand the growth of strained AlGaInAs by MBE for laser applications. A total of 4 laser wafers have been processed under this program. Three wafers produced working lasers and one exhibits pulsed lifetest performance beyond any measured in the history of this company. Lifetest data is still being collected for laser array CW operation.

The laser array performance seen is superior to any array made by this company to date. The light output for a given operating current does not degrade at up to 10^8 pulses. In fact, output rises slightly because threshold falls under operation.

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Strained AlGaInAs semiconducting material for improved laser performance

Contents

Summary

The Phase I program is almost completed. A minor amount of lifetest data is still being collected. This program has been successful at demonstrating for the first time that strained AlGaInAs quantum well lasers grown by MBE can exhibit superior reliability to AlGaAs quantum well lasers. The benefits to device performance justify undertaking the development of a commercial process to bring this improved reliability to the market for DOD applications. A phase II proposal is being prepared.

There were 11 quantum well wafers characterized to help guide the selection of optimum growth conditions and to understand the growth of strained AlGaInAs by MBE for laser applications. A total of 4 laser wafers have been processed under this program. Three wafers produced working lasers and one exhibits pulsed lifetest performance beyond any measured in the history of this company. Lifetest data is still being collected for laser array CW operation.
Figure 1 is a plot of the lifetest performance of a strained AlGaInAs quantum well laser array fabricated and tested under the Phase I program. This result is essentially the summary conclusion of the Phase I program. The laser array performance seen here is superior to any array made by this company to date. The light output for a given operating current does not degrade at up to 10^8 pulses. In fact, output rises slightly because threshold falls under operation. The reason for a fall in threshold with operating time is not clear. A "burn-in" for laser arrays to improve their performance is without precedence. Burn-in of individual laser stripes has been seen before. This behavior requires study to see how it may be applied to improved laser array reliability.

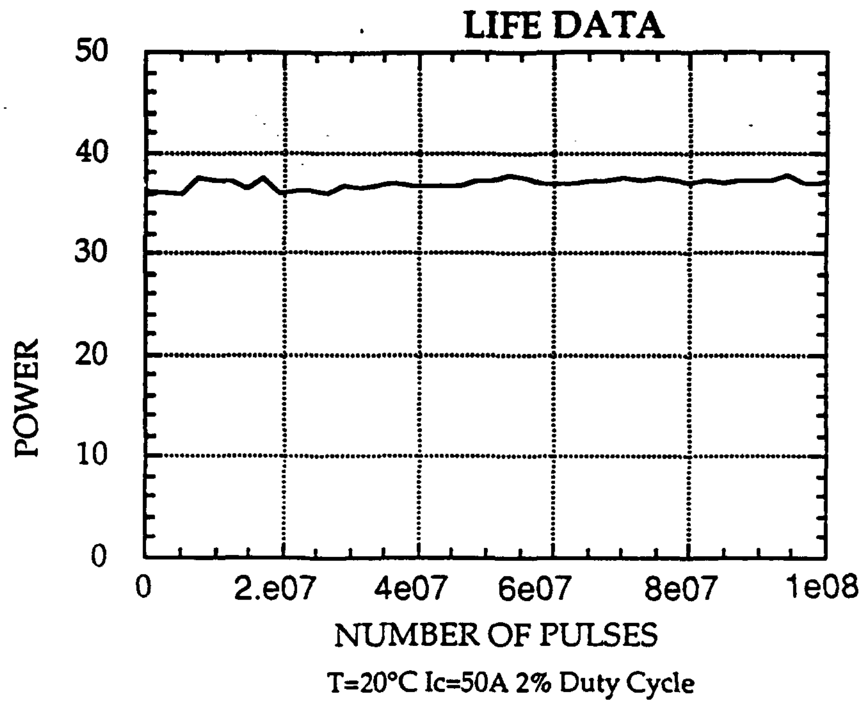

Figure 1. Lifetest data for strained AlGaInAs quantum well 808 nm laser

Phase I Program Review.

Relevance to Phase I Proposal

The Phase I program followed the proposal quite closely. Monthly evaluations were made and some program alterations took place. They were explained in monthly reports. A fundamental inefficiency of the operations of this company, the separation of MBE growth and laser fabrication facilities in different cities, was successfully addressed in the Phase I program. Visits between personnel in both locations took place on three occasions to ensure successful technical exchange. These intensive reviews resulted in the discovery of a number of MBE growth problems which existed despite more than 2 years experience in the Roanoke MBE facility. The benefits of the Phase I research extend beyond the Phase I program and will assist existing research and production.

A second benefit beyond the direct program goals was improved technology transfer between Cornell University and Northeast Semiconductor. Basing the Phase I proposal on areas of mutual interest to both organizations provided a natural opportunity to share information and materials for analysis. The samples from previous research at Cornell provided quantitative comparisons of radiative recombination efficiencies which gave new insights into the operation of the Varian GEN II MBE machines in Roanoke. The existing programs at Cornell on strained layer laser research will continue to provide insights into a proposed Phase II program and into Phase III. The proposed Phase II program will likely spin off benefits to the company beyond the development of a commercial laser growth process for improved array reliability. The spinoff benefits of improved operation of the MBE machines was one important Phase I unanticipated result.

Phase I Technical Performance

There are two general areas studied in Phase I. They are: 1) strained AlGaInAs quantum well growth and characterization for growth condition development and 2) laser wafer growth, laser array processing and packaging and array test.

Strained AlGaInAs quantum well growth and characterization

Three different series of strained quantum well growths were performed. They were grown to try to develop optimized growth conditions and gather data to describe indium desorption from AlGaInAs as a function of substrate temperature in order to develop design rules for composition control and laser wavelength control. These goals were largely met, but design rules are only partially complete. A summary of indium desorption data is seen in quantum well emission wavelength versus substrate temperature seen in figure 2.

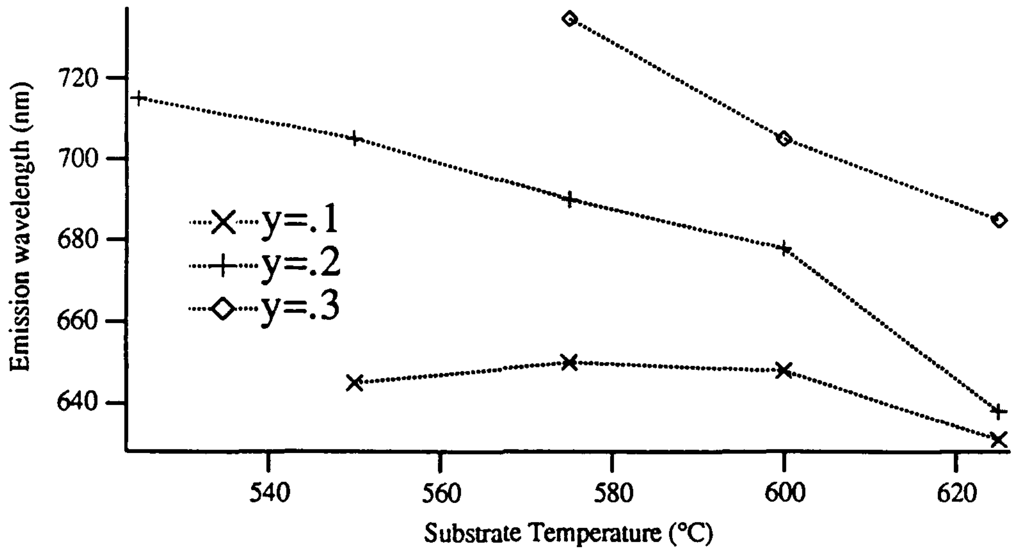

Figure 2. 4K PL Emission wavelengths from 3 AlGaInAs quantum wells as a function of substrate temperature

Additional study is needed to turn this data into design rules for being able to accurately predict laser wavelength as a function of structure and growth condition. This data is sufficient to guide further study which should take place through actual laser wafer growths and array fabrication.

The early quantum well growths showed the expected results that strained AlGaInAs quantum wells exhibited best performance when grown at higher temperatures than those used for strained GaInAs. This behavior is analogous to the differences in optimum growth conditions for GaAs when compared to AlGaAs. The difficulty with increased substrate temperature growth for AlGaInAs growth is desorption of indium, similar to desorption of Ga from AlGaAs. The solution to controlling desorption of Ga from AlGaAs is to grow the material at temperatures below 640°C, the congruent sublimation temperature (T_{CS}) for GaAs. This solution does not seem like it would apply to growth of AlGaInAs since substrate temperatures below T_{CS} to avoid indium desorption leads to poor quantum efficiency. Desorption of indium will have to be carefully documented to permit accurate modelling and reproducibility of compositions. The data from these growths is documented in the monthly reports and will not be reproduced here.

The quantity and quality of data from the quantum well growths fell short of expectations in one respect. The strained AlGaInAs quantum wells required sufficient alteration to structure and growth conditions from those planned in the proposal that a number of samples did not provide luminescence. This result is surprising based on the experience at Cornell with strained GaInAs/GaAs quantum wells prior to the Phase I study. The addition of aluminum to GaInAs resulted in material with significantly different quality for the initial growth conditions studied. Although growth conditions were eventually discovered to get data from these structures, too many growths were void of quantitative data to complete the data base needed for developing design rules.

Future efforts to collect data sufficient to develop design rules for strained AlGaInAs quantum well lasers should come from the growth and processing of actual laser structures and not from quantum well photoluminescence. Since laser thresholds cannot be predicted from simple quantum well PL, actual lasers would provide more data relevant to laser development than further quantum well growths. Laser structures could be characterized as to threshold current, quantum efficiency, wavelength and reliability. Laser wavelengths would provide information on the effect of growth conditions on quantum well composition. Since growth conditions would be expected to play a role in reliability, they should be developed by direct comparison with array characterization. When enough comparison of laser properties and laser wafer PL are made, it may be possible to use PL as a pass/fail evaluation of grown wafers prior to the expense of laser array processing to evaluate the quality of the wafer.

Laser characterization would begin with PL measurements of the as-grown laser wafer. This technique was employed for the laser structures studied in Phase I. PL provides advance knowledge of laser wavelength. Laser emission is usually about 12 nm longer in wavelength than PL from as grown laser structures. Photoluminescence from every wafer grown in Phase I was discussed in the monthly reports. It was seen that intensities were inferior to PL intensity from the same, or similar structures, to those grown at Cornell. The reasons for inferior quality were determined to be:

1. Inadequate machine purity
2. Errors in setting substrate temperatures
3. Non-optimum arsenic/gallium flux ratio

Machine Purity

The unintentional impurity concentrations in MBE grown wafers arise largely from the background impurities in the MBE machine. Although the impurity concentrations are not sufficient to alter laser performance resulting from excessive ionized impurities, radiative recombination is very sensitive to the quality of the grown layers which can be dramatically affected by impurities. It is well know that oxygen, water, CO and $C0_2$ all cause defects in growth of AlGaAs which are responsible for non-radiative recombination. Oxygen and the oxygen in water readily react with Al. The same behavior is thought to come from oxygen in CO and CO2. Carbon is also known to incorporate as a result of exposure to these gases. Carbon on the growing surface of AlGaAs reduces the surface mobility of Al which is already small compared to Ga, therefore AlGaAs is especially sensitive to the presence of background impurities.

Unintentional gases are removed in greatest number by baking the entire MBE machine at 200°C after exposure to air which is the source of these impurities. Impurities would otherwise slowly outgas from the machine walls at slow rates for an unacceptably long time. Higher temperature baking is more effective, but the high temperature limit of such MBE parts as the Viton O-rings in valves does not permit higher total machine temperatures. Individual components, however, can be baked hotter. Those which collect contamination which will be liberated when they are heated up for normal MBE use need to be baked hotter than the rest of the machine. This procedure which has been standard at Cornell, but has not been followed at the Roanoke production facility.

Laser growths at Roanoke have historically resulted in low yields of good wafers. The first few wafers following machine bakeout have always been of poor performance. The reason is likely to be contamination by atmospheric gases which were not sufficiently removed during bake out.and become free when components are heated up for the first time. The primary source of this form of contamination seems to be the substrate heater station. The substrate heater elements are among the hottest components when the machine is growing a wafer. They adsorb atmospheric gases which have substantial vapor pressures at the heater temperatures which are well beyond 1000°C in order to heat a substrate to 600-700°C.

The solution to removal of this contamination is to run the heater to outgas it prior to growing materials. The best opportunity to run the substrate heater up in temperature is during bakeout so that the impurities liberated at higher temperature will not stick to the hot walls of the machine and desorb to contaminate the layers at a later time. A bakeable cable had to be constructed to permit this operation. This has been done during Phase I. The effect of baking the substrate heater during bakeout has not been tested in laser growth yet.

This procedure has also been applied to the furnaces. Following the MBE growths made for Phase I, the eight machine furnaces are now brought up to 400°C (except for arsenic - 150°C) after the bakeout has begun and the pressure has fallen. The titanium sublimation pump further undergoes pregrowth bakeout and is idled at high temperatures during bakeout. Both of these sources previously produced large amounts of outgassing prior to, and during the first few growths. It is not known how long it took to remove all of this contamination, nor whether the new procedure is effective at meeting this goal. This procedure is now identical to that practiced at Cornell.

One last action taken to improve wafer purity, and radiative recombination efficiency is removal of excess arsenic which has built up in the machine. This arsenic will soak up atmospheric contamination when it is at atmosphere. Slow outgassing of this contamination is undesirable. The machine was opened and approximately one pound of arsenic was scraped from its walls, or vacuumed from the bell jar sump.

Substrate temperature set point errors

Reproducibility of the lasers was compromised by previous assumptions about the relationship between substrate temperature measured by the thermocouple and actual substrate temperatures. It had been assumed that the actual temperature differed from the thermocouple by an offset and 1:1 correspondence near the growth temperatures used. Calibration of the offset occurred by observation of the reflection high energy electron (RHEED) pattern to find the setting of temperature where reconstruction indicates that the substrate is at the congruent sublimation temperature (T_{CS}). It was determined by use of the pyrometer over an extended range that the actual correspondence was other than 1:1 after determining what offset occurred at 640°C. The actual relationship has been determined to be approximately 3° substrate temperature change for 5° change in thermocouple. This change is now properly handled by modification of the growth automation software to permit slope and offset values to be used in calculations.

Arsenic flux set errors

A second contribution to substrate temperature measurement errors, in addition to other material quality ramifications was arsenic flux setting. The quality of III-V materials by MBE can be strongly influenced by V/III flux ratios. RHEED is the essential tool in establishing the proper value of arsenic flux for growth of GaAs and AlGaAs so that they exhibit the highest radiative recombination efficiency. A growth procedure at Roanoke began by using this technique to calibrate proper arsenic flux, but had become neglected over time. Reproducing pressure ratios was substituted as a calibration procedure. This technique is inadequate because ion gauges used for pressure calibration will change in sensitivity to different compounds because of deposition of materials on them. As a result, non-optimum III/V values were used. The RHEED observations are now the sole calibration for III/V flux selection.

In addition to poor III/V ratio choices, group III pressure readings were used to establish growth rate. This technique also suffers from the problem of changing ion gauge sensitivity. The result of group III flux errors was the growth of materials with uncalibrated growth rates and compositions. Reproducibility in composition and thicknesses suffered from growth with an uncalibrated system. RHEED oscillation measurements of growth rates have been reinstituted as the sole growth rate calibration procedure. The reason for drifting away from the procedures which have had to be reinstituted is that they require additional time to perform which reduces machine throughput. The tradeoff between yield and throughput has been compared through this experience and the need for additional calibration at the expense of throughput is now clearly established.

All of these changes in procedures are the result of Phase I study. Although the changes occurred over the span of the program, they were not completely implemented until after the end of wafer growths. It is anticipated that Phase II efforts would benefit substantially from this work, and that some level of additional development would characterize Phase II experiments. The goal of bringing this MBE machine up the performance of the machine used for comparison at Cornell has been met

Strained AlGaInAs quantum well laser characterization

The end goal of Phase I is to demonstrate that strained AlGaInAs lasers can be grown by MBE. It was hoped at the onset, and proved in Phase I study, that the addition of In to AlGaAs quantum wells results in improved laser array reliability. The three classes of measurements which were performed on the laser arrays in this program are: 1) optical power versus current (PI), 2) laser spectral measurements, and 3) operating lifetest measurements.

Two different laser structures were studied in Phase I. The structure which most closely resembles AlGaAs graded index separate heterostructure (GRINSCH) single quantum well (SQW) laser arrays presently fabricated is seen in figure 3. It was grown previously and was processed into laser array bars under this Phase I study. The growth conditions were chosen to be closely compatible to present laser growths. The clad and graded AlGaAs regions were grown at 710°C and the substrate temperature is dropped to 550°C for the strained AlGaInAs growth. Growth interruptions on either side of the quantum well are used for substrate temperature changes.

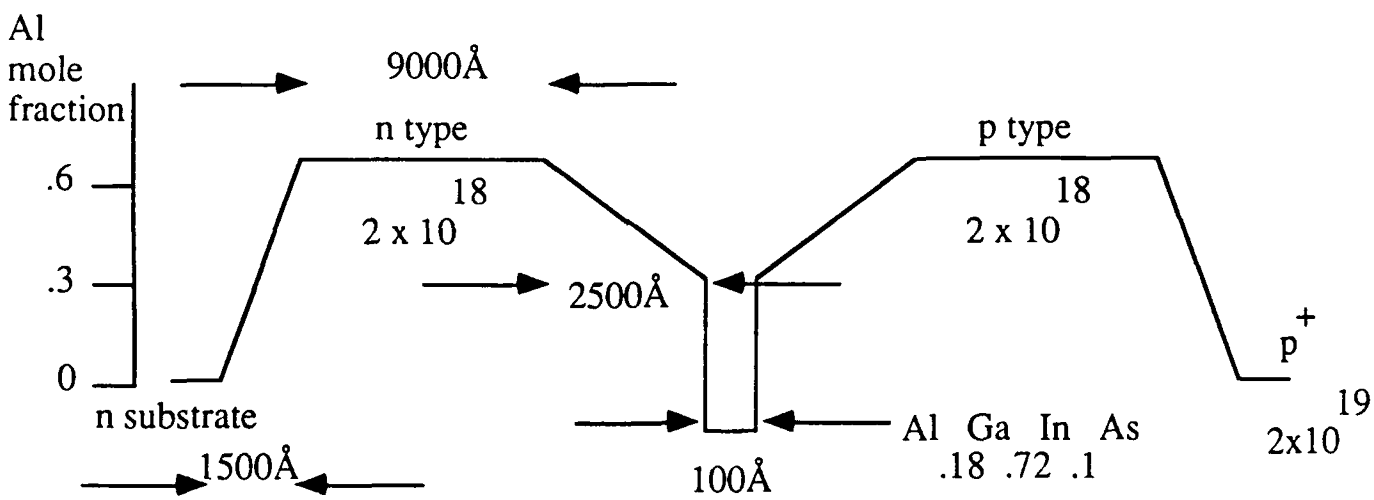

Figure 3. Standard GRINSCH - structure 1.

An alternative structure was studied also. It is seen in figure 4. This structure was grown 3 times at different substrate temperatures for the quantum wells of each growth. The structure has 2 quantum wells. The amount of indium used was the highest studied, and therefore had the thinnest critical thickness possible for quantum wells.Two quantum wells were used for comparison to laser wafers grown at Cornell for high speed modulation with strained GaInAs quantum wells in otherwise identical structures. The GRIN region was replaced with abrupt change in

Al composition as the confinement factor for 2 quantum wells for this structure would combine to have a similar confinement factor to the standard GRINSCH SQW laser.

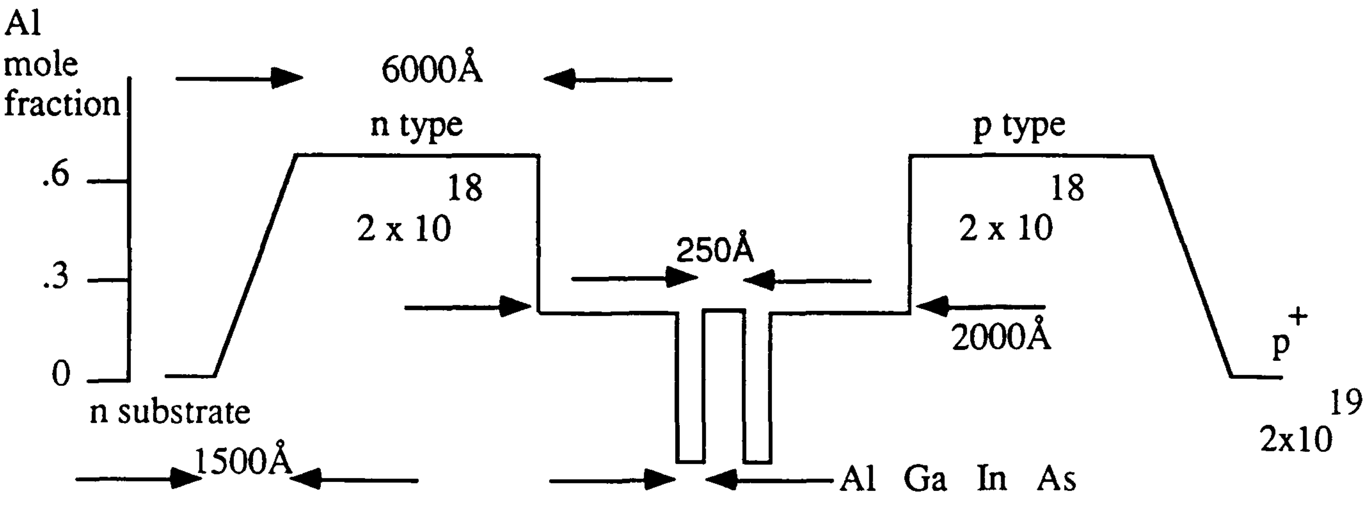

Figure 4. Alternative double Quantum Well - structure 2.

PI

The optical power (P) and voltage (V) versus current (I) of the two different classes of laser structures were measured under pulsed conditions. A 200 µsec pulse at 100 Hz is used to avoid heating of the diode laser arrays. The pulsed PI and IV characteristics for the two different classes of lasers are seen in figures 5 and 6. The GRINSCH SQW (structure 1) has a QW grown at 550°C while the 3 other lasers have quantum wells grown at 550°C, 575°C and 600°C. The structure grown at 600°C did not lase, while the 550°C and 575°C structures were identical in performance except for wavelength.

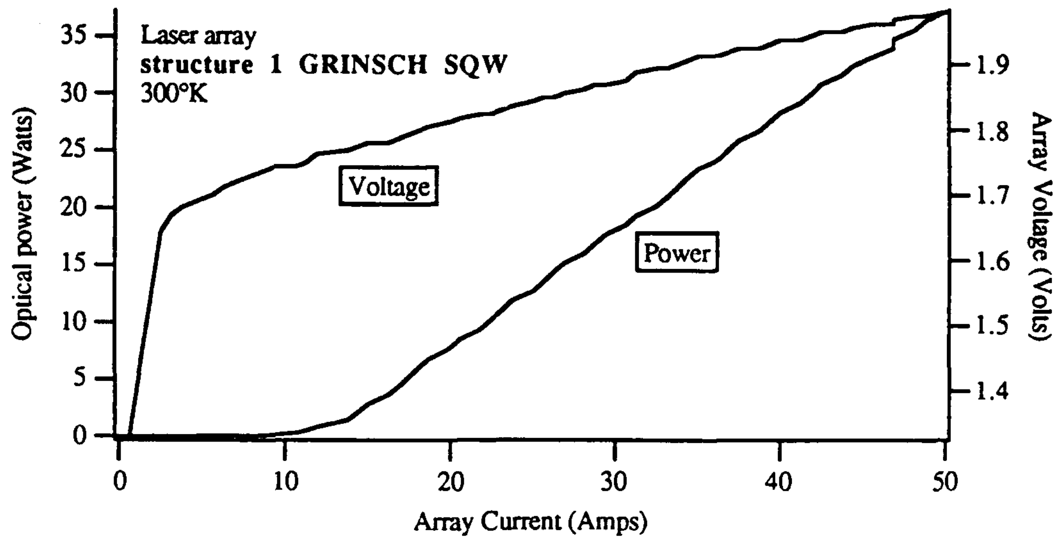

Figure 5. PI and VI characteristics of GRINSCH SQW laser array - structure 1

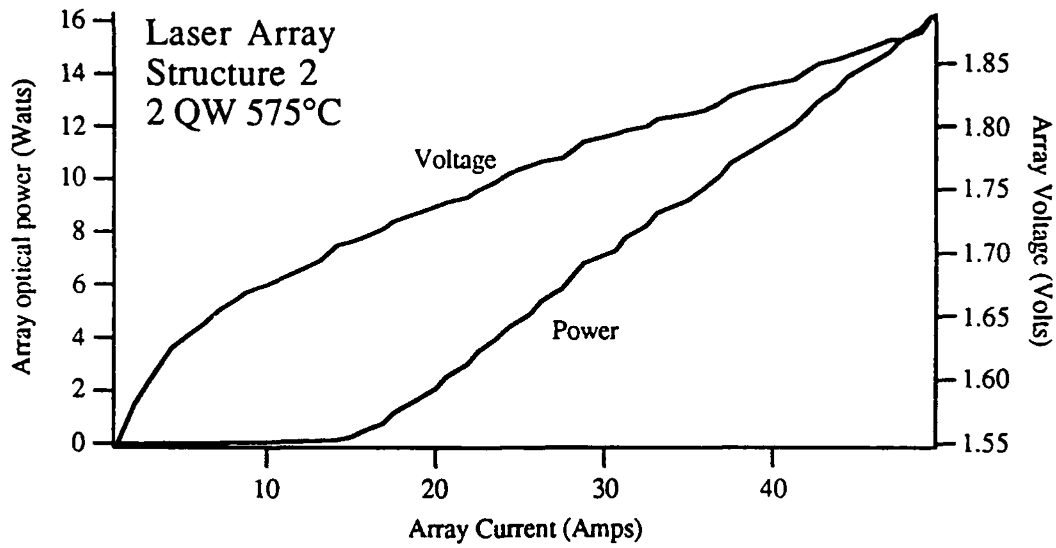

Figure 6. PI and VI characteristics of 2 QW laser array - structure 2

Spectral Measurements

A typical array spectrum is seen in figure 7. An important feature of the spectrum is the full-width half maximum (FWHM) measurement of the wavelength uniformity of the diodes which make up the array. The FWHM of this array is less than 4 nm which is excellant for solid state laser pumping applications.

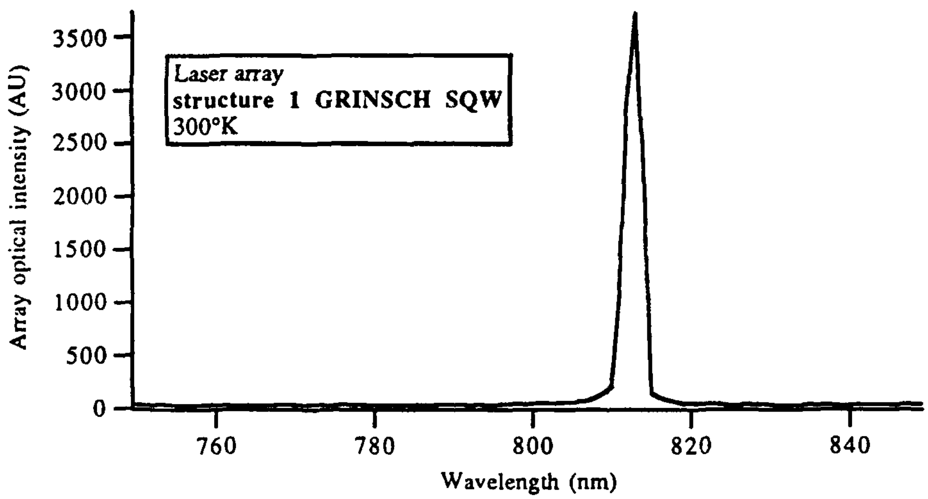

Figure 7. Typical array spectrum.

Lifetest

The most important finding sought under Phase I study is enhanced reliability of strained AlGaInAs lasers under lifetest characterization. The lifetest for the best result (the SQW GRINSCH) laser has already been shown in figure 1. This performance is proof of the potential of these laser arrays when grown by MBE. The2 QW laser structure has had lifetime measurements performed for comparison to the GRINSCH SQW structure. Lifetest data is shown in figure 8.

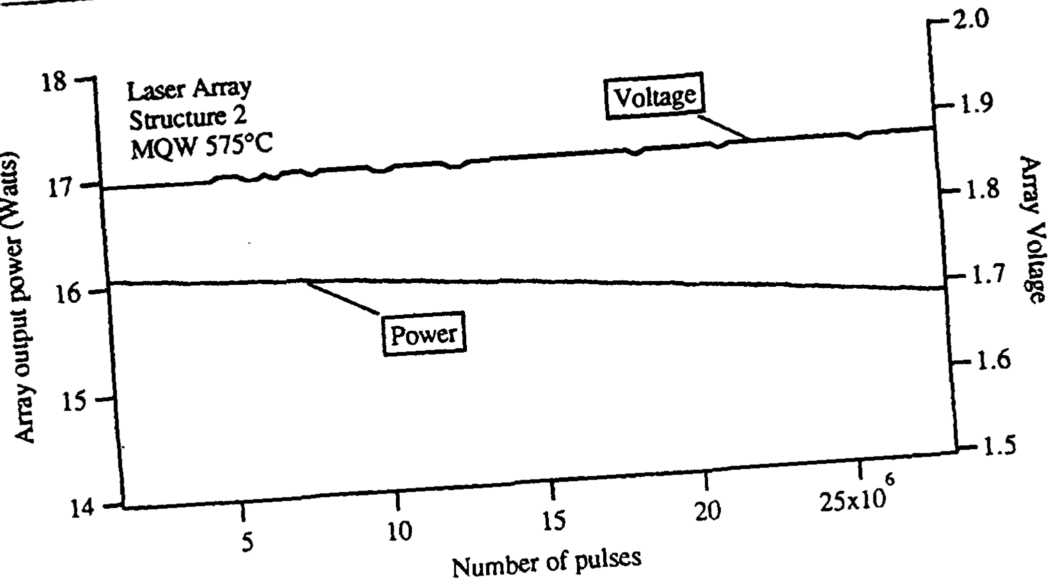

Figure 8. Lifetest data from 2 QW laser structure; QWs grown at 575°C

Conclusions

The Phase I study was successful in its demonstration of improved reliability of strained AlGaInAs quantum well lasers. The fundamental growth studies of strained AlGaInAs/AlGaAs quantum wells established some preliminary information about the effect of growth conditions on these materials. The next step in optimizing growth conditions for these structures requires considerable study. A Phase II study will be proposed.